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DETECTION OF BASE SEPARATION IN 175MM ARTILLERY SHELL BY GAMMA-RAY TRANSMISSION

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The feasibility of gamma-ray transmission to inspect for base separation between the steel shell and the high explosive casting in 175 mm projectiles was explored. The method consists of passing the section of the projectile containing the metal base-explosive interface across a highly collimated beam of cobalt-60 gamma rays and measuring changes in transmission with a scintillation detector. It is demonstrated both theoretically and experimentally

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that a 30-mil (0.030 in.) gap can be detected using rigidly controlled laboratory conditions with a mock projectile and an artificially induced separation. This technique was also tested with 100 fully loaded projectiles. The presence of an actual base separation was not positively identified in this very small sampling of shells. However, two projectiles showed abnormal gamma-ray scan profiles. Upon sectioning, these indicated the presence of anomalies at the base region. The method is concluded to be sufficiently sensitive to detect base separation in artillery shell but requires further development to be adaptable to high speed production line inspection.

ACKNOWLEDGMENT

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INTRODUCTION

Separation of the high explosive bursting charge from the base of the steel projectile has long been considered a primary cause for premature detonations of the larger caliber artillery shell. The accepted theory presumes adiabatic heating of entrapped air or vapors in the resulting gap, leading to the explosive initiation of the charge before the projectile leaves the gun barrel. Nondestructive inspection for the presence of base separation--as well as for other critical defects in the high explosive charge--is a desirable goal, in particular for a method which lends itself to rapid automatic use in ammunition loading lines. Ideally the inspection system should be fully automatic. It should require neither human operators nor human decision making for the accept-reject process.

In a recent Southwest Research Institute (SWRI) survey of automated radiographic inspection techniques as applied to artillery shell it was concluded that "the state of the art of image acquisition (i.e. film radiography) is not adequate to the requirement. Although a fully automated system using conventional radiographic film as an image forming medium is feasible, the intermediate chemical development step and the densitometric scanning steps make it entirely too slow; moreover, the operating cost would probably be prohibitive" (Ref 1). A similar assessment was made for "filmless imaging devices including fluorescent screens, x-ray sensitive TV vidicons, electroluminescent panels, etc" in that "none was found having the basic required resolutions, sensitivity or effective response to x-rays or gamma rays of energy high enough to effectively penetrate the steel shell."

The SWRI survey also indicated that the most promising approach to an inspection system for critical defects in the H.E. charge is direct radiation gauging or the use of a highly collimated beam of penetrating radiation to scan the item and measure the transmitted signal with a detector on a real-time basis. The inadequacy of film and filmless imaging methods and the potential of radiation gauging had already been established at Picatinny Arsenal and is supported by the SWRI conclusions. This report describes the results of an experimental study designed to test the radiation gauging approach for the inspection of 175 mm projectiles for the presence of base separation.

GAMMA-RAY TRANSMISSION METHOD

The method is based on the transmission of a narrow or very thin beam of gamma radiation from a cobalt-60 source through the section of the projectile containing the interface of the steel base and explosive (Ref 2). The attenuation of monoenergetic gamma rays on passing through this interface in the presence of a base separation or an air gap is governed by the theoretical relationship:

$$I/I_o = e^{-\mu_s \rho_s t_s} \; e^{-\mu_e \rho_e t_e} \; e^{-\mu_a \rho_a t_a} \qquad (1)$$

where

I_o = intensity of gamma rays incident on the projectile

I = intensity of gamma rays passing through the projectile

μ_s, μ_e, μ_a = the gamma-ray energy absorption mass attenuation coefficients for steel, explosive, and air, respectively, for gamma rays of specific energy

ρ_s, ρ_e, ρ_a = density of steel, explosive, and air, respectively

t_s, t_e, t_a = thickness of steel, explosive, and air, respectively, traversed by the beam.

Equation (1) is accurate only for gamma rays of a specific energy. A typical gamma-ray spectrum from cobalt-60 radiation passing through a 175 mm projectile as measured with a 2 in. diameter x 2 in. thick sodium iodide scintillation detector is shown in Figure 1. For this particular study, a single-channel analyzer was used to process the signal from the detector. An electronic filter or base line was set in the valley just below the 1.17-MeV energy peak. All energies above this level were counted and by assuming an average energy of 1.25 MeV, the condition of monoenergetic gamma rays is approximated. In this manner one can eliminate the need for a build-up factor in Equation (1). Such a factor is normally required to account for lower energy radiation scattered into the detector (Ref 3).

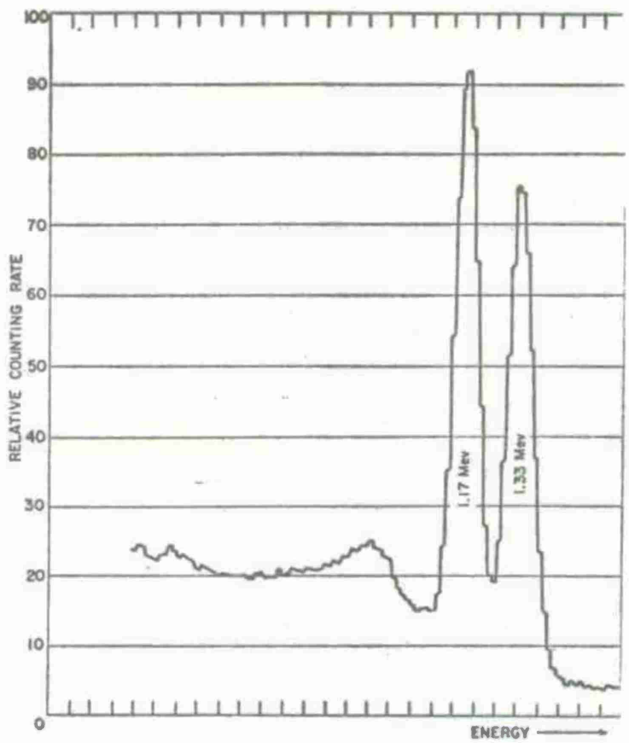

Fig 1 Cobalt-60 gamma-ray spectrum

EXPERIMENTAL EQUIPMENT

Mock Projectile

A dimensioned cross section of a mock projectile fabricated to simulate controlled conditions for experimentation is shown in Figure 2. The item was an actual 175 mm steel shell base cut in two pieces parallel to the base; these cut surfaces were carefully machined. The "explosive" is a removable wax simulant approximating the density of the actual explosive, Comp B. The wax was cast in this particular shell base, thus making it a precisely seated match for the steel-explosive interface to be studied. Air gaps of known dimensions were introduced by placing stock metal shims between the two machined steel parts of the shell base, thus raising the "explosive" insert a fixed distance above the interface. Dimensions of the projectile given in Figure 2 are in inches. Mil spec tolerances are indicated for certain critical dimensions.

Gamma-Ray Gauge Assembly

A sketch and photograph of the gamma-ray gauge assembly with the mock projectile in place are shown in Figures 3 and 4, respectively. The gauge assembly is mounted on a specially designed table to support the weight of the necessary lead and concrete shielding. The adjustable elevator platform which supports the 175 mm round at the center of the gauge is operated by a mechanical gear and screw arrangement. This allows the shell to be raised or lowered through the gamma beam in small controlled increments. A micrometer dial affixed to the table measures the relative shell height position to the nearest thousandth of an inch. A large lead block positioned at one side of the "elevator" contains a hole in the top into which the radioactive cobalt-60 source can be placed. A micrometer screw is mounted on a movable 1/2-inch-wide lead block insert which enables the operator to open this lead block slit in one-thousandth of an inch increments for the cobalt-60 radiation beam to pass. On the opposite side of the shell, a similar large lead block is mounted, with a hole machined into one end to house the detector. A similar micrometer screw and movable 3/4-inch-wide lead block slit arrangement allows the detector slit to also be operated in thousandths of an inch increments. The bases of the two slits are optically aligned so that the beam of radiation can pass through to the detector.

A 45-millicurie cobalt-60 source, stainless steel encapsulated, is bolted onto an adjustable plastic jig (not shown) for insertion into the "source hole" in the lead block. This allows the source to be precisely positioned in the slit for maximum radiation transmission. With the source in position an additional shield consisting of a combination of lead bricks and concrete blocks (not shown in Figure 4) is placed around and under the assembly on the table to maintain a permissible level of radiation for the operator.

The shell position indicator was placed so that the dial reading would approximate 500 mils when the steel-explosive interface was in the beam. Readings could then be taken up to 1/2 inch above and below this point. Experiments showed that relative readings of 500 ± 150 mils were sufficient to obtain data.

Counting Instrumentation

Conventional Nuclear Instrument Module (NIM) counting equipment was used to process the gamma-ray signal from the scintillation detector. This includes a preamplifier, linear amplifier, single-channel analyzer and a combination timer and digital scaler. Approximately 900 volts used to bias the multiplier phototube of the detector were provided by a 3000-V power supply.

As stated earlier, the single-channel analyzer was used to set the lower baseline in the valley below the 1.17-MeV cobalt-60 energy peak (Fig 1). All signals from events above this level were counted. This eliminates all low energy scatter from Compton gamma rays and lead x-rays. The shell is moved in increments of a few thousandths of an inch and a series of timed counts are taken at each position.

RESULTS

Theoretical Calculations

A theoretical analysis as to the feasibility of the gamma-ray transmission approach was performed prior to any experimental effort. From geometric and trigonometric relationships, expressions for the values for t_s, t_e, and t_a in Equation 1 were calculated in terms of height, h, above the base of a typical projectile. Using the tolerances as given in Figure 2, these values for t would assume maximum and minimum values for each position h. Setting $I_o = 1$, relative values for I were calculated for a shell with (a) no base separation and (b) an assumed air gap between base and explosive of 0.030 inch, as a function of height above the bottom of the base (h) as h increased in 0.005-inch increments. A summary of the expressions and the appropriate constants used is given in Appendix A. The Picatinny Arsenal CDC-6500/6000 Computer was used for the routine computations.

The result of this theoretical analysis is shown in Figure 5. Four individual plots of Equation 1 are reproduced with the abscissa expressed in actual heights above the bottom of the base starting with a fixed point in the solid steel portion of the base. For a fixed height above the base, each pair of points shown represents the relative count rate for the maximum and minimum thickness, respectively, of projectile through which the gamma-ray beam is being transmitted. For this particular "theoretical" shell, the steel-explosive interface is at a point 1.212 inches above the bottom of the base. Starting slightly above this point, for the case of the assumed air gap, the relative count rates are consistently higher than for the case of no gap. The maximum increase is at a point about 0.030 inch above the interface and the magnitude of this difference is about 15%. It is important to note that there is no overlap of signal between the curves representing the minimum thickness of the case for no gap and the maximum thickness of the case with the gap. From this analysis, it was considered justifiable to proceed with the experimental feasibility study.

Experiments with Mock Projectile

A series of experiments was performed on the mock 175 mm projectile using the gamma-ray transmission gauge with and without an induced 0.030-inch air gap to simulate base separation. Considerable effort was required to optically align the collimator slits and cobalt-60 source for maximum signal transmission and optimum resolution. This was accomplished by trial and error. A summary of this data is given in Figure 6 wherein each experimental point is the mean of at least five or more 100-second counts. The abscissa in Figure 6 represents relative position along the vertical axis of the projectile as read from the micrometer dial indicator (Fig 3 and 4). Total height of scan covered by the experimental points is actually only 0.15 inch. The steel-explosive interface occurs at about 0.550 inch above the base in the mock shell. Count rates are net with the background count at each point obtained with the collimator slits completely closed to measure the amount of radiation reaching the detector not transmitted through the slits. This background signal, in the order of 50 counts per second, was subtracted from the gross signal. On this basis a direct comparison can be made between the theoretical data of Figure 5 with the experimental data of Figure 6. With respect to the general shape of the curves and the magnitude of difference in transmitted gamma-ray signal between the case of no base separation with that of an air gap, the theoretical and experimental sets of data are quite similar. Thus, the relationships as given by Equation 1 are shown to hold reasonably well using this gauge assembly and mock projectile under controlled laboratory conditions.

Results with Actual 175 mm Projectiles

In the last phase of this investigation, 100 projectiles, fully loaded with Comp B but defused, were tested with the experimental gauge in the same manner as was the mock shell. For these runs, gross count rates were recorded, with a 200-second count at each point. The count rates for these shells are generally lower in magnitude because of the higher density of the actual explosive as compared to the mock explosive. Relative shell positions as obtained from the dial indicator are also different because of variations in dimensions among individual projectiles. The important consideration from the scan of each shell is the shape and slope of the data points obtained. Figure 7 represents a typical set of data obtained for most of the 100 projectiles. Several of these were sectioned with no apparent sign of base separation. This type of scan profile was arbitrarily designated as "normal" for a satisfactory projectile. An abnormal scan profile was obtained for the projectile as shown in Figure 8. Once beyond the steel-explosive interface, the count rates are decidedly higher than "normal," possibly indicating base separation. When this shell was sectioned, irregularities such as nobs and depressions were observed in the metal base at the interface with the explosive. Another anomalous scan profile is represented by the shell in Figure 9. When this shell was sectioned, a fluid or exudate material was found at the base.

DISCUSSION

Premature detonations in guns occur in fewer than one out of a million firings. The testing of 100 projectiles is therefore statistically only a very small sampling. Nevertheless, the fact that two projectiles were isolated and upon sectioning were found to contain an obvious anomaly in the metal base-explosive interface does demonstrate the high degree of sensitivity of the gamma-ray transmission method. It must be cautioned, however, that the tests performed in this study were under very carefully controlled conditions using relatively long count times at each point of scan. For actual production loading lines, each shell will require scan speeds in the order of a few seconds or less to inspect not only for base separation but for other defects as well in the entire high explosive casting. Such inspection rates will require a cobalt-60 source in the curie strength range instead of the millicurie range used here. This high intensity source requirement is not by itself a major problem. It only requires more extensive radiation shielding. The more challenging technical problems are associated with the ability to interpret the signal at such high scan rates with a fully automated computerized system. Another important requirement will be availability of suitable standards with well-defined critical defects to facilitate the accept-reject decision making process. Considerable development and design efforts are required at this stage to satisfy these goals.

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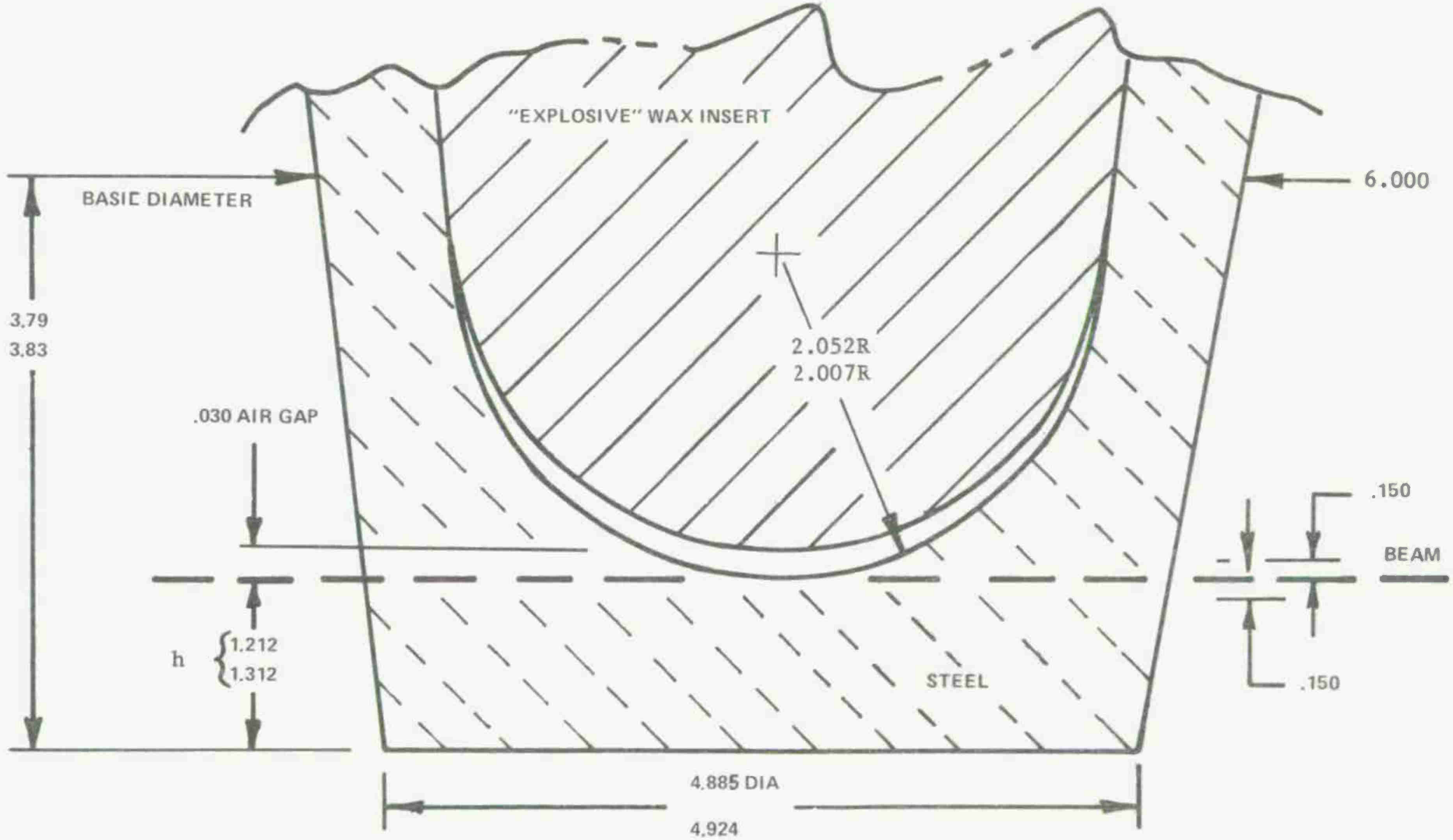

Fig 2   175 mm shell base cross-section with separation

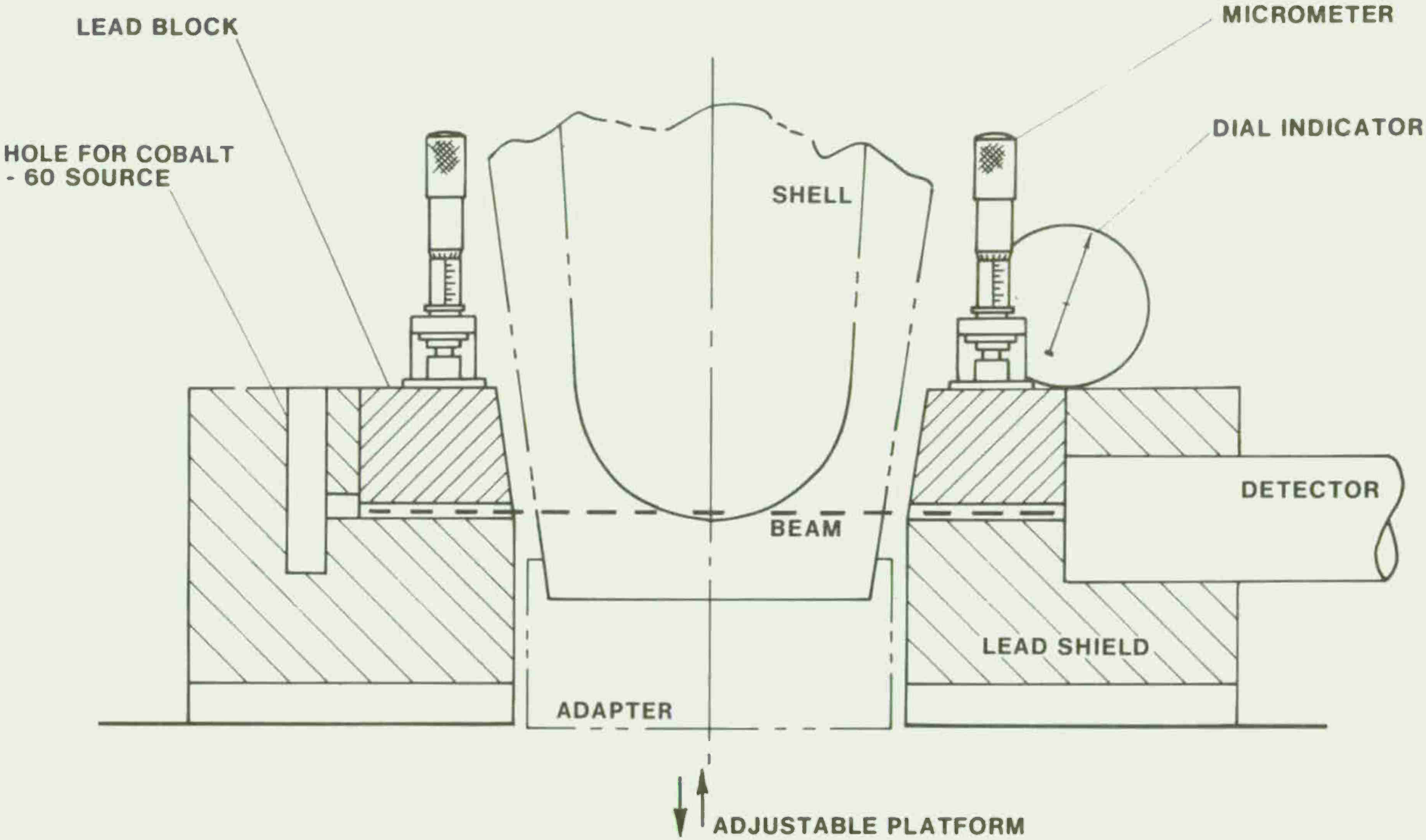

Fig 3 Collimator prototype - gamma-ray assembly with 175 mm shell base

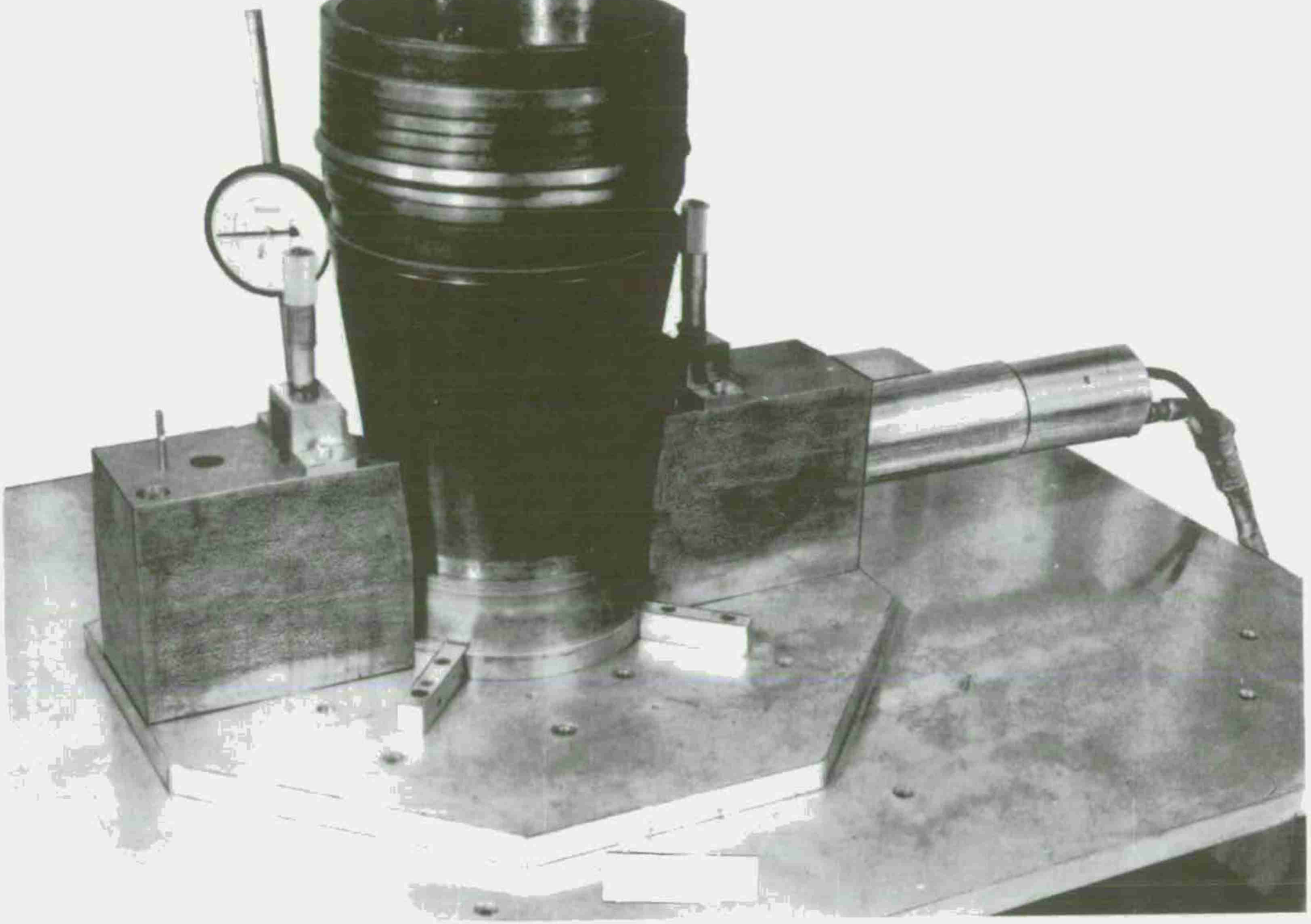

Fig 4   Collimator prototype - gamma-ray
gauge assembly with shell base

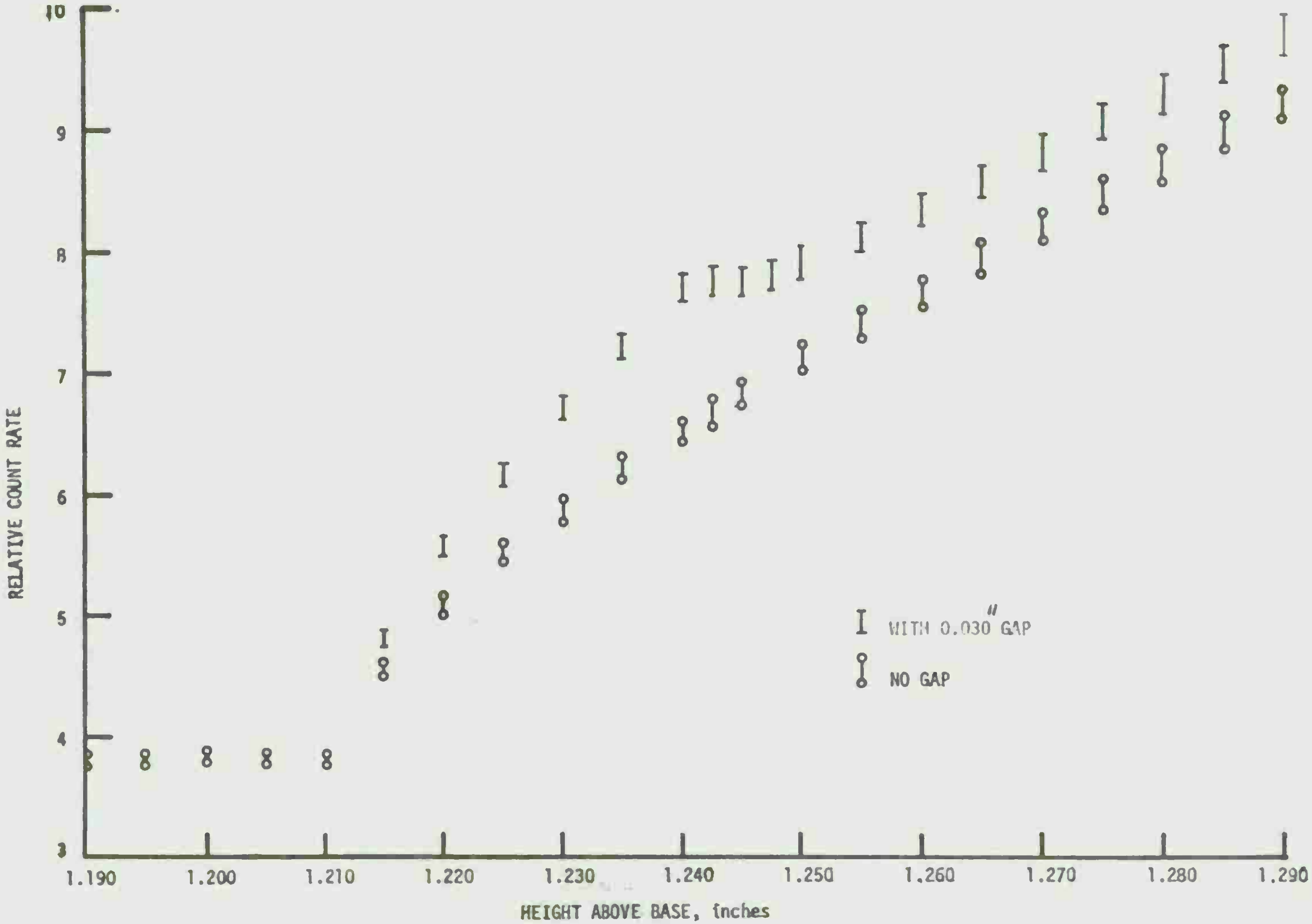

Fig 5 Theoretical relative count rate (I/I_0) as a function of height above base for the 175 mm projectile

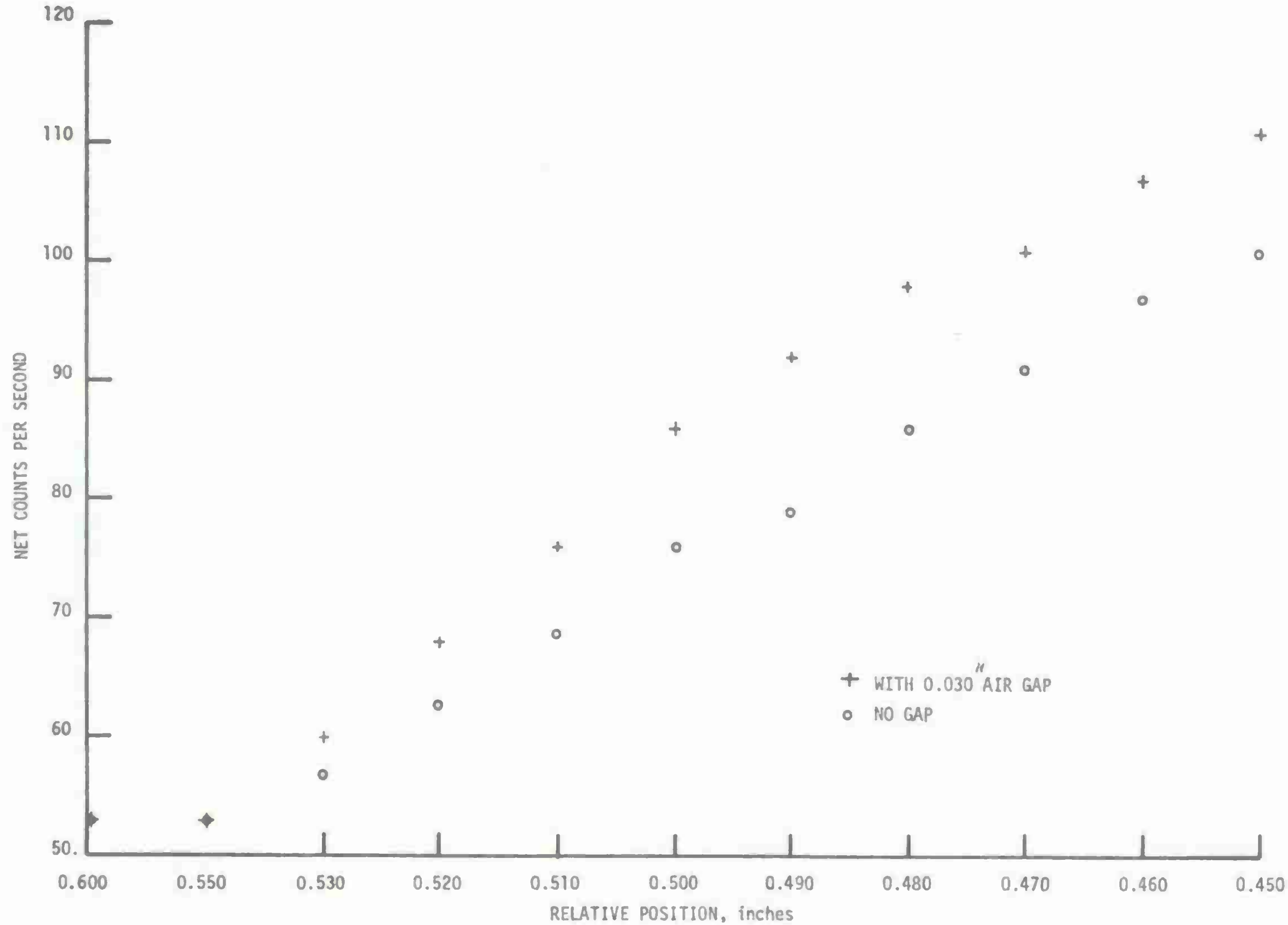

Fig 6 Count rate as a function of relative position for a "dummy" 175 mm projectile with and without base separation

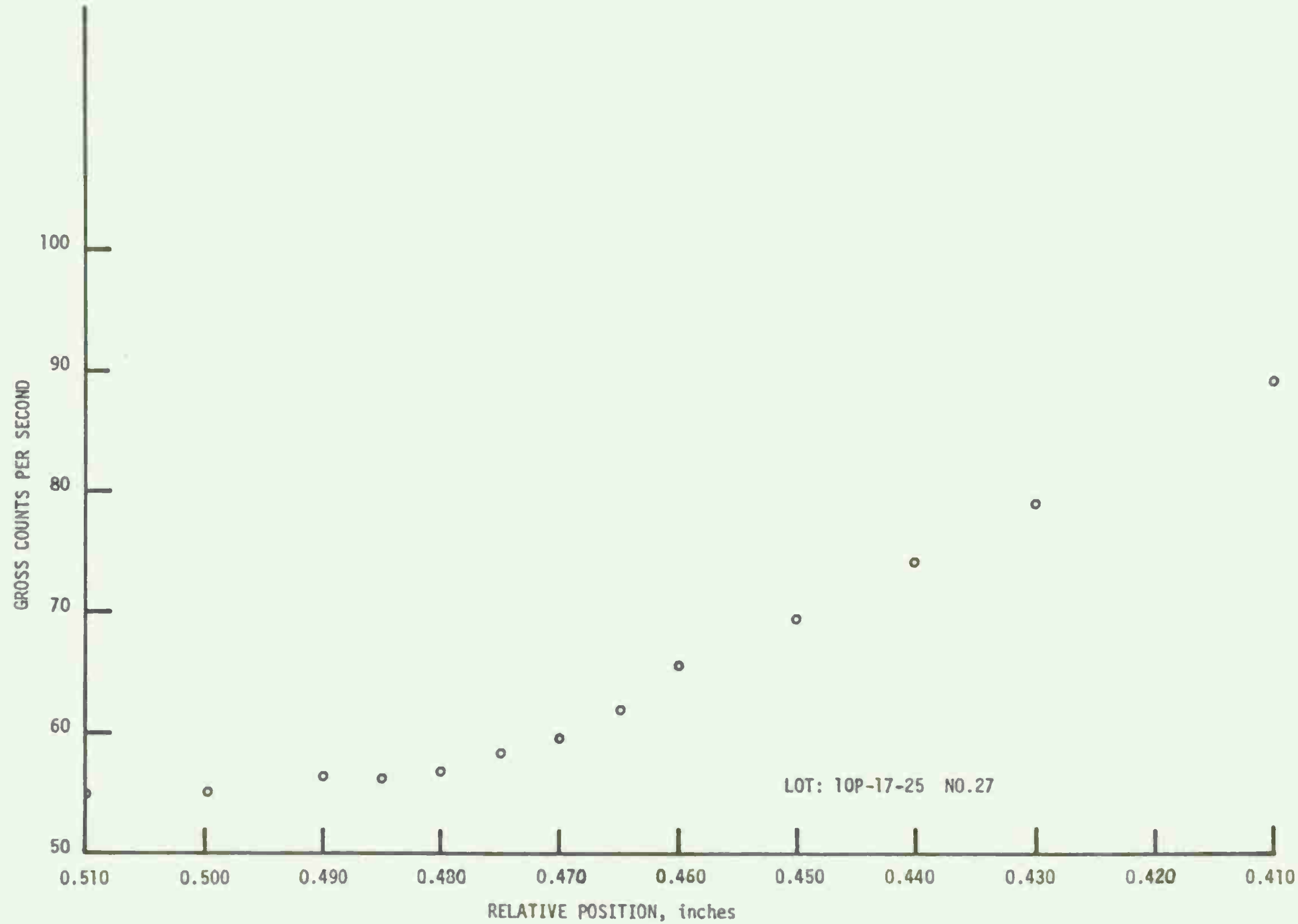

Fig 7 Count rate as a function of relative position for a "normal" 175 mm projectile

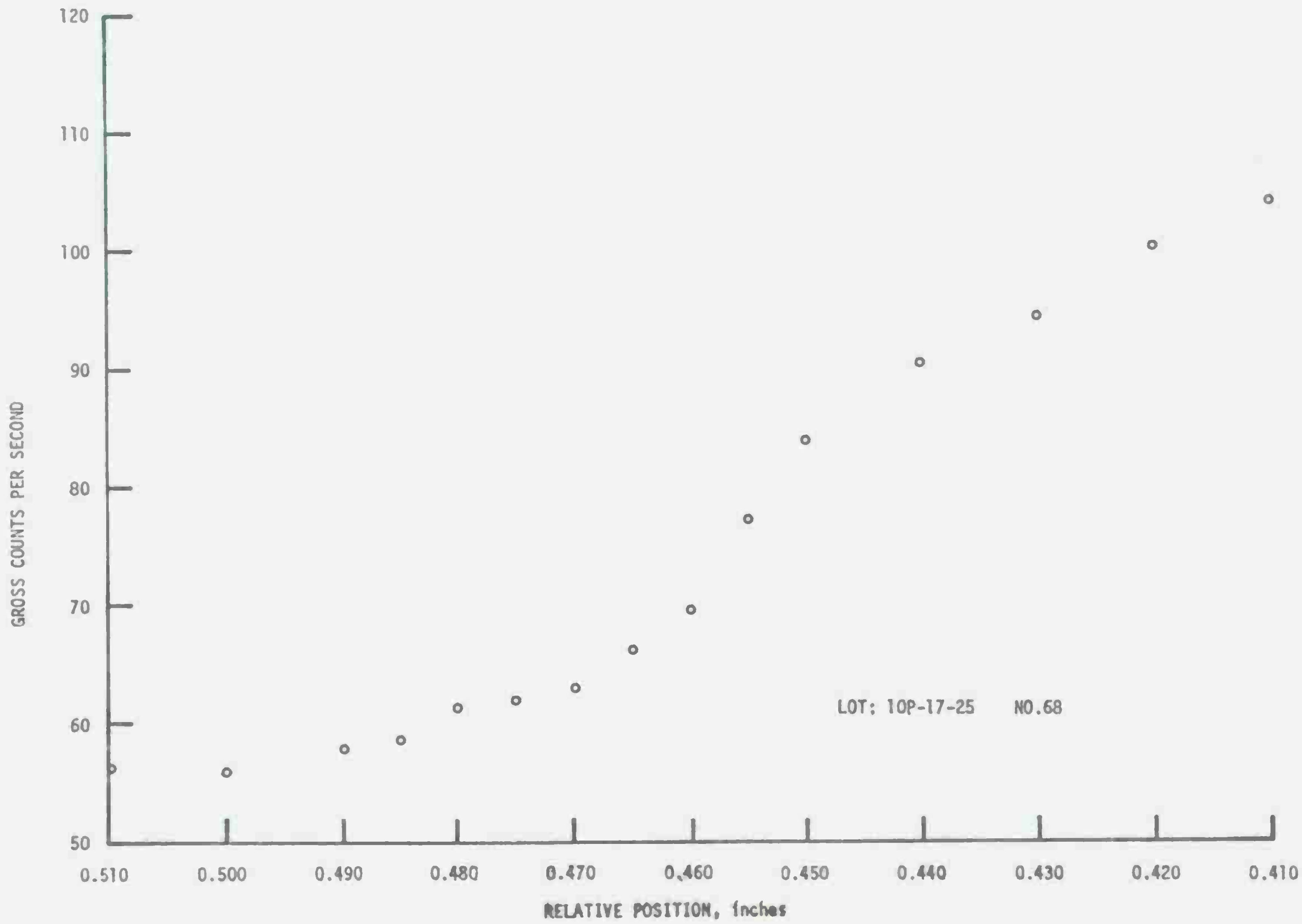

Fig 8 Count rate as a function of relative position for a 175 mm projectile with "irregularities" at the base

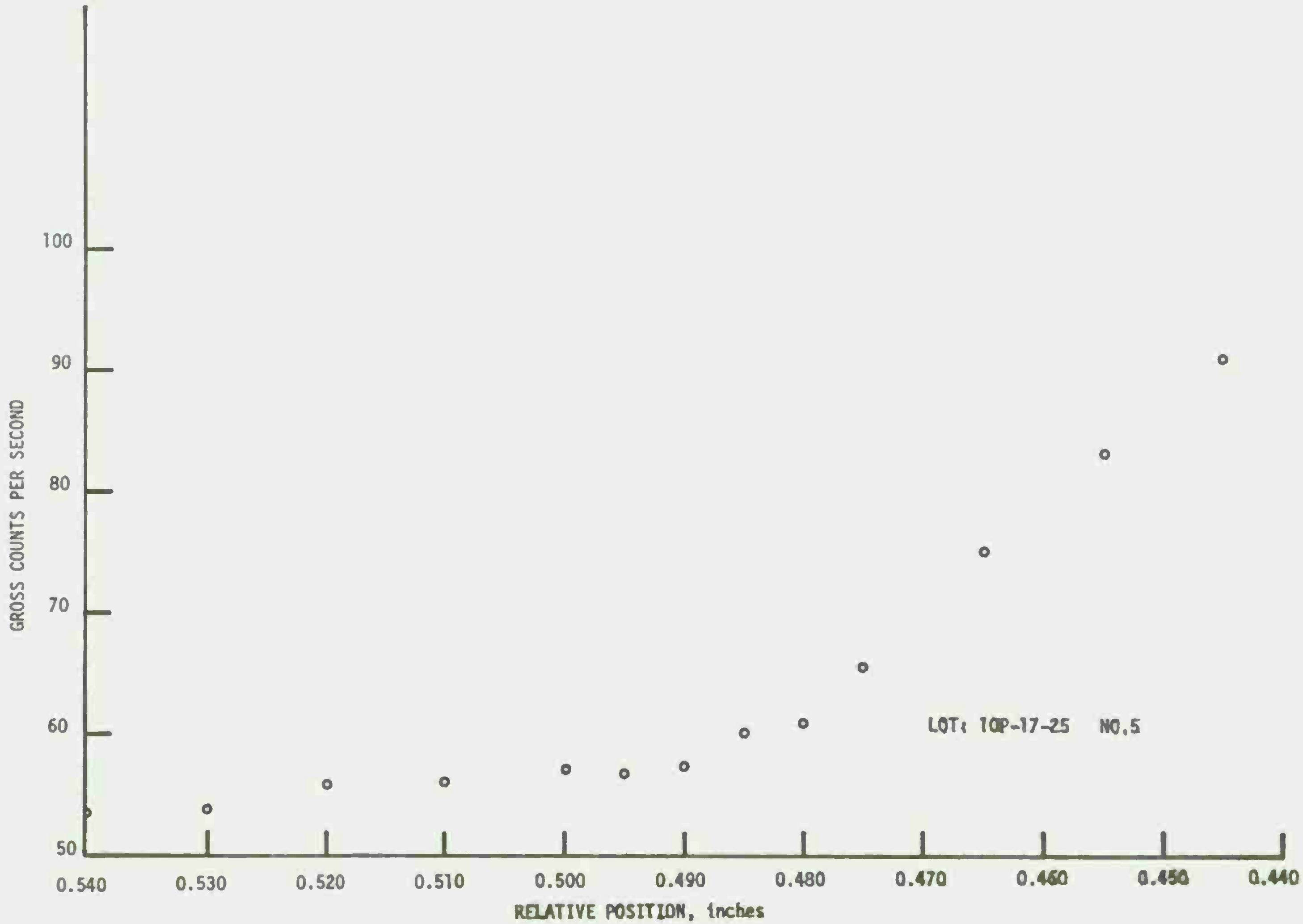

Fig 9 Count rate as a function of relative position for a 175 mm projectile with fluid material found at base

APPENDIX A

GEOMETRICAL CALCULATIONS FOR GAMMA-RAY ABSORPTION

The theoretical shell must fit the limits of the maximum and minimum dimensions given in the specifications. These dimensions were taken or calculated from drawing no. 10520195, "175 mm Projectile."

For each height, h, above the base, a family of curves could be drawn for a maximum and minimum thickness of each related variable. Logic dictates that for the maximum transmission of radiation through the shell, the thickness of the steel must be a minimum and the thickness of the explosive and/or air a maximum.

Because the height above base of the interface of the steel shell body and the spherical cavity which contains the explosive can also vary within tolerances, the minimum value of h (equal to 1.212 inches), and thus, the minimum thickness of steel, would give the maximum transmission of radiation. For this condition to be met, the diameter of the base of the shell must be a minimum. The height of the basic diameter above the base must also be a minimum to make the radius of the internal spherical cavity a maximum.

Using dimensions given and geometrical considerations to calculate other needed dimensions, the maximums and minimums shown in Figure 2 were computed. To solve the minimum transmission, the same logic is used, by transposing the words minimum and maximum in all statements above, except for the constant minimum value of h = 1.212 inches.

To complete the theoretical curve family, these equations must be solved for the two conditions required, that is with a 0.030-inch air gap and with no air gap. The equations are solved while moving up into the shell in 0.005-inch increments starting at 1.100 inches above the base and moving through the interface at 1.212 inches to 1.500 inches above the base. This insures "seeing" the entire air gap and moving far enough into the explosive filler beginning at 1.242 inches above the base. The four equations for an interface at 1.212 inches above the base are then for the maximum and minimum thickness of steel, with an air gap of 0.030 inch and with no air gap.

In the equation: $\frac{I}{I_o} = e^{-\mu_s \rho_s t_s} \; e^{-\mu_e \rho_e t_e} \; e^{-\mu_a \rho_a t_a}$

for 1.25 MeV gammas:

$$\mu_{air} = 0.0567\ cm^2/g \quad \rho_{air} = 0.001\ g/cm^3 \quad \therefore\ \mu_a\rho_a = 0.00014/inch$$

$$\mu_{expl} = 0.0570\ cm^2/g \quad \rho_{expl} = 1.70\ g/cm^3 \quad \therefore\ \mu_e\rho_e = 0.2461/inch$$

$$\mu_{steel} = 0.0531\ cm^2/g \quad \rho_{steel} = 7.86\ g/cm^3 \quad \therefore\ \mu_s\rho_s = 1.0602/inch$$

Let $I_o = 1$; in each case calculate I for h = 1.100 to 1.500 in 0.005-inch increments.

For maximum steel, no air gap

$$I = e_s^{-1.0602\ [(4.9242 + 0.2809h)-(2\sqrt{-6.9879 + 6.6382h-h^2})]}$$
$$e_e^{-0.2461\ (2\sqrt{-6.9879 + 6.6382h-h^2})}$$

For minimum steel, no air gap

$$I = e_s^{-1.0602\ [(4.8853 + 0.2941h)-(2\sqrt{-6.4425 + 6.5276h-h^2})]}$$
$$e_e^{-0.2461\ (2\sqrt{-6.4425 + 6.5276h-h^2})}$$

For maximum steel, 0.030 inch air gap

$$I = e_s^{-1.0602\ [(4.9242 + 0.2809h)-(2\sqrt{-6.9879 + 6.6382h-h^2})]}$$
$$e_e^{-0.2461\ (2\sqrt{-7.1880 + 6.6982h-h^2})}$$
$$e_a^{-0.00014\ (2\sqrt{-6.9879 + 6.6382h-h^2} - 2\sqrt{-7.1880 + 6.6982h-h^2})}$$

For minimum steel, 0.030 inch air gap

$$I = e_s^{-1.0602\ [(4.8853 + 0.2941h)-(2\sqrt{-6.4425 + 6.5276h-h^2})]}$$
$$e_e^{-0.2461\ (2\sqrt{-6.6392 + 6.5876h-h^2})}$$
$$e_a^{-0.00014\ (2\sqrt{-6.4425 + 6.5276h-h^2} - 2\sqrt{-6.6392 + 6.5876h-h^2})}$$

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